REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
06-23-2014	Proceedings	01-01-2013-12-31-2013

4. TITLE AND SUBTITLE

Workshop on Micro and Nano Structures for Phase Change Heat Transfer

5a. CONTRACT NUMBER

5b. GRANT NUMBER

N00014-13-1-0324

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Evelyn N. Wang

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

77 Massachusetts Ave. 3-461B, Cambridge, MA 02139

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

ONR, 875 N. Randolph Street, Ships and Engineering Systems Division, Code 331, Arlington VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)

ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

000146

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release: distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The workshop seeks to identify critical challenges, advancements, and new directions for micro and nano structures in phase-change research. The panels and presentations in this two day focused workshop was structured to provide ample opportunities to educate researchers from different fields on topics related to this important subject and to seek their engagement in developing a clear pathway to advance pertinent fundamental knowledge and technologies.

15. SUBJECT TERMS

phase-change workshop

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Evelyn N. Wang
					19b. TELEPHONE NUMBER *(Include area code)*
					617-324-3311

Proceedings: Workshop on Micro and Nano Structures for Phase Change Heat Transfer

Boiling, evaporation, and condensation on micro and nano engineered structures have received significant interest over the last decade. These structures on surfaces hold great promise to advance liquid-vapor phase change systems and are important to enable thermal management of ultra-high heat flux systems, such as computer processing units (*CPUs*), laser diodes, and power amplifiers. Accordingly, there has been a substantial increase in research efforts in these areas with a significant emergence in recent publications, workshops, and conferences. However, a comprehensive understanding of complex phase-change processes is still needed to harness these processes for a range of devices and critical applications. To address these shortcomings and to provide a roadmap to industry, government agencies, and the academic communities, a group of approximately 100 experts from the fields of mechanical engineering, chemical engineering, and material science engineering experts met for a two day workshop in the *MIT*'s Endicott House to attend the *Workshop on Micro and Nano Structures for Phase Change Heat Transfer*. The agenda is also included on pages 3-4. The roadmap aims to define the pathway for future generation phase-change technologies.

Based on the discussion during the workshop the following recommendations were proposed by the attendees:

1. **Consolidation of current research knowledge through rigorous and technical identification of what is known and unknown.** It is likely that the debates in the field are associated with ambiguity about flow regimes. A detailed mapping and careful review is needed to collectively advance fundamental scientific understanding. One approach is to select a critically important rudimentary problem or several problems (e.g., flow boiling in a micro gap under specific heat/flow/surface conditions) and bring together experts from several key disciplines (e.g., experiments, modeling, metrology, uncertainty quantification, electronics, and microfabrication) to work on this well-defined problem and form standardized benchmark results. Careful and extensive characterizations of the experimental system and operating conditions are needed. Scrutinization of all of the experimental and modeling aspects will be carried out by independent parties. The results will serve as the baseline results for any future use.

2. **Establishment of a research hub to provide microfabrication and experimental know-how.** This approach will provide reliable research results on fundamental problems pertinent to microscale and nanoscale heat transfer. Funding for such an initiative can partly be supported through existing mechanisms, such as DURIP, NSF Major Research Instrumentation (MRI)

program, summer/sabbatical faculty internship, MEMS Exchange, regular research grants, fellowships, etc. While receiving support from the participating agencies (e.g., NSF, ONR, DARPA, ARPA-E), the principal investigators working in the field can partly administrate their research through this research hub.

3. **Expanding the community.** Bringing in new expertise and researchers with interdisciplinary fields that are interested in addressing problems in phase change heat transfer to make breakthroughs. They can provide additional insights and create new research opportunities by introducing new characterization tools, experimental methods, fabrication capabilities, and general "out of the box" thinking. Pairing heat transfer experts with others for joint funding opportunities could be an impetus.

4. **Longevity of the community.** Creating an ongoing forum (i.e., conference or workshop) to discuss scientific and engineering advancements in the area of micro and nano structures for phase change heat transfer.

5. **Technology transfer.** Addressing practical commercialization concerns, such as reliability and robustness, are essential. Increased involvement with industry could accelerate progress to define the key issues. Furthermore, involving more industry in forums or consortiums would be helpful.

In addition, slides from the workshop were uploaded on our website http://micronano.mit.edu/outcomes.html. Furthermore, a special issue in the journal *Nanoscale and Microscale Thermophysical Engineering* (NMTE) has been written by the workshop participants and will appear in the July 2014 issue.

Agenda

Monday, April 22, 2013 (7:30 am-8:30 pm)

Goal: Familiarize the community with challenges and state-of-the art research; Identify needs and opportunities for micro/nanostructures in phase-change research

7.30-8.45: Registration and breakfast
8.45-8.55: Welcome and opening remarks
8.55-9.10: Modern history of enhanced heat transfer surfaces
9.10-11.20: Needs and future trends for enhanced phase-change heat transfer
Moderators: Dr. Terry Hendricks, Battelle and Dr. Srinath Ekkad, Virginia Tech
9.10-9.25: David Altman, Raytheon
9.25-9.40: Dr. Peter DeBock, General Electric
9.40-9.55: Dr. Shankar Devasenathipathy, Intel Corporation
9.55-10.10: Dr. Avi Bar-Cohen, DARPA
10.10-10.25: Dr. Mark Spector, Office of Naval Research
10.25-10.40: Dr. James Klausner, ARPA-E
10.40-10.55:NSF
10:55-11.10: Panel discussion with industry and government presenters
11.10-11.20 Break
11.20-12.30: State-of-the-art boiling research
Moderators: Dr. Sushil Bhavnani, Auburn University, Dr. Vinod Narayanan, Oregon State University, Dr. Weilin Qu, University of Hawaii
11:20-11:45: Overview talk: Dr. Michael Jensen, RPI
11:45-12.30: Discussion with panelists: Dr. Satish Kandlikar, RIT, Dr. John Thome, EPFL, Dr. Jungho Kim, University of Maryland
12.30-1.30: Lunch
1.30-2.40: State-of-the-art thin film evaporation research
Moderators: Dr. Chen Li, University of South Carolina, Dr. Shalabh Maroo, Syracuse University, Dr. Youngsuk Nam, Kyunhee University
1.30-1.55: Overview talk: Dr. Andrei Fedorov, Georgia Tech
1.55-2.40: Discussions with panelists: Dr. Suresh Garimella, Purdue University, Dr. Bill Ma, University of Missouri, Dr. Joel Plawsky, RPI, Dr. Peter Stephan, TU Darmstadt
2.40-3.00: Break
3.00-4.10: State-of-the-art condensation research
Moderators: Dr. Kripa Varanasi, MIT, Dr. Chuan-Hua Chen, Duke, Dr. Jorge Alvarado, Texas A&M
3.00-3.25: Overview talk: Dr. Ryan Enright, Bell Labs
3.25-4.10: Discussions with panelists: Dr. Tony Jacobi, UIUC, Dr. John Rose, University of London, Dr. Srinivas Garimella, Georgia Tech
4.10-4.25: Roadmap guideline discussions
4.25-5.15: Breakout discussions
5.15-5.30: Collective discussions
5.30-6.30: Poster Session
6.30: Banquet

Tuesday, April 23, 2013 (8:30-5:00)

Goal: Introduce broader perspective of opportunities from other related fields and summarize overall workshop. Offer roadmap for phase-change heat transfer for next decade

8.30-9.00: Breakfast
9.00-9.50: Surface chemistry and surface science
Moderators: Dr. Diana Borca-Tasciuc, RPI, Dr. Konrad Rykaczewski, NIST/MIT
9.00-9.25: Perspectives: Dr. David Quere, ESPCI, Dr. Van Carey, UC Berkeley, Dr. Daniel Attinger, Iowa State University
9.25-9.50: Discussion
9.50-10.40: Materials, fabrication, and manufacturing approaches
Moderators: Dr. Matthew McCarthy, Dr. Luc Frechette,
9.50-10.15: Perspectives: Dr. CJ Kim, UCLA, Dr. Nikhil Koratkar, RPI, Dr. John Hart, U of Michigan/MIT
10.15-10.40: Discussion
10.40-10.55: Break
10.55-12.00: Modeling methods and opportunities
Moderators: Dr. Mario Trujillo, University of Wisconsin, Madison, Dr. Onkar Sahni, RPI, Dr. Abhijit Mukherjee, Cal State Northridge
10:55-11.20: Perspectives: Dr. Yogi Joshi, Georgia Tech, Dr. Paul Keblinski, RPI, Dr. Jayathi Marthy, UT Austin, Dr. Assad Oberai, RPI
11.20-12.00: Discussion
12.00-1.00: Lunch
1.00-2.10: Measurement methods and instrumentation
Moderators: Dr. Carlos Hidrovo, UT Austin, Dr. Saeed Moghaddam, University of Florida, Dr. Aaron Schmidt, Boston University
1.00-1.25: Perspectives: Dr. Jacopo Buongiourno, MIT, Dr. David Cahill, UIUC, Dr. Li Shi, UT Austin
1.25-2.10: Discussion
2.10-2.25: Break
2.25-3.25: Breakout sessions
3.25-3.40: Break
3.40-5.00: Summaries of breakout sessions
5.00: Concluding remarks